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The impact of shading design and control on building cooling and lighting demand

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Abstract

Shading should be considered as an integral part of fenestration system design for commercial and office buildings, in order to balance daylighting requirements versus the need to reduce solar gains. In this paper, the simultaneous impact of glazing area, shading device properties and shading control on building cooling and lighting demand was calculated using a coupled lighting and thermal simulation module. The interactions between cooling and lighting energy use in perimeter spaces were evaluated as a function of window-to-wall ratio and shading parameters. An exterior roller shade was used as an example. The impact of shading device type, properties and control on building cooling and lighting energy demand was quantified and analyzed. The simulation results indicate that, if an integrated approach for automatic control of motorized shading is used in conjunction with controllable electric lighting systems, substantial reduction of energy demand for cooling and lighting could be achieved in perimeter spaces, depending on climatic conditions and orientation.

Keywords: Daylight maximization; Shading design and control; Electric lighting consumption; Cooling demand; Hourly simulation

1. Introduction

Building design is a complex process during which critical decisions concerning the different systems related to the building are made at the early stage. For perimeter spaces, an integrated thermal and daylighting analysis is required, since the two domains are inter-related. Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting (Lee et al., 1998; Tzempelikos and Athienitis, 2002), while the benefits in terms of higher productivity of office workers are also high (Heschong, 2002). Nevertheless, large fenestration areas often result in excessive solar gains and highly varying heating and cooling loads. In addition, intense daylight leads to glare problems, especially for south-facing facades of office buildings.

Advanced glazings and innovative daylighting/shading systems are being studied in order to control solar gains, reduce glare and create a high quality indoor environment. A major factor in the evaluation of the performance of such devices is their detailed optical and thermal characterization. These properties are usually not provided by manufacturers and there is no standard procedure for measuring them. Moreover, in most simulation tools, they are considered constant (independent of solar incidence angles). They can be estimated using experimental techniques (Rosenfeld et al., 2001; Andersen et al., 2005;

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Collins et al., 2001), using detailed theoretical models (Pfrommer et al., 1996) or using advanced software (Reinhart and Walkenhorst, 2001). Tools such as WIS (van Dijk, 2002) and Parasol (Wall and Bullow-Hube, 2002) provide valuable sources of measured data for a variety of glazing and shading products.

Driven by technological advances in transparent building facades, design alternatives have shifted to utilizing dynamic fenestration and shading systems for optimal control of daylighting and solar gains. Recently, with significant architectural developments, the advantages of daylighting have been re-identified and the need for detailed simulation programs that integrate thermal and daylighting performance is strong (Selkowitz, 1998). As a result, some researchers have coupled daylighting and thermal simulation (Franzetti et al., 2004). Performances of glazing systems based on integrated simulation with widely used software are described by Citherlet and Scartezzini (2003). Presently, building performance can be accurately predicted using building energy simulation programs. Some programs (i.e., ESP-r, Energy Plus) link daylighting and thermal simulation in an integrated manner (Clarke et al., 1998; Crawley et al., 2002). Traditionally, the approach followed was to estimate solar gains and internal gains from lights and equipment, which would contribute to space cooling load.

However, the potential for dynamic operation of shading devices through a building automation system is generally neglected. The impact of shading design and control on building performance is not taken into account at the design stage, although an optimum cooling and lighting energy balance between fenestration and lighting may be identified and utilised (Lee and Selkowitz, 1995). Recent studies have shown that appropriate shading design and control, when linked with simultaneous control of electric lighting and HVAC components, could significantly reduce peak cooling load and energy consumption for lighting and cooling, while maintaining good thermal and illuminance indoor conditions (Tzempelikos and Athienitis, 2003; Johnson et al., 1984). However, this is only possible by carefully selecting fenestration and shading properties and control, taking into account their combined impact on lighting and thermal performance of perimeter spaces and then optimizing their operation. The main problem is that the current integrated building simulation software are used to evaluate the overall energy performance of existing buildings, or hopefully, in the design development stage, when the building form is already determined. The reason is that detailed input data is required in order to run even the simplest simulation. Consequently, the selection of final design solutions concerning fenestration often involves many subjective factors imposed by the design team at the early stage.

A general simulation design methodology for integrated daylighting and thermal analysis of perimeter spaces of commercial buildings was therefore developed (Tzempelikos, 2005). The objective was to provide guidelines on how to select glass ratio of the façade, shading device properties and control. This paper presents representative results about fenestration and shading analysis and design at the early stage using this methodology. First, window-to-wall ratio is selected based on integrated performance indices obtained by the continuous interaction between transient hourly thermal and lighting simulation. Daylight availability ratio and reduction in peak thermal loads and energy consumption are identified as major initial criteria. The impact of different shading properties on daylight availability and overall energy performance of perimeter spaces of office buildings is shown using simulation and the significance of control strategies is discussed.

2. Selection of window size

A simulation sensitivity analysis was performed to investigate the effect of window size and orientation on combined daylighting and thermal performance of perimeter office buildings. Previous studies (Ghisi and Tinker, 2005) showed that window areas recommended for view should be revised in order to lower energy consumption. A study for Swedish offices (Bullow-Hube, 1998) confirmed the significant and complex impact of glazing type and size on heating and cooling demand. In the present study, a typical ($4\,m \times 4\,m \times 3\,m$ high) private perimeter office space in Montreal was used as a base case. The effect of window size on electric lighting demand was also studied. If the electric lights are controlled, electricity consumption is further reduced; the impact of automatic control of dimmable lighting on cooling load was also investigated. Results allow the selection of window size for each orientation, based on priority criteria. Window size is expressed as window-to-wall ratio (WWR) for generalization of results. Initially, three factors were considered for selection of window-to-wall ratio of the façade: (i) the ability to provide adequate daylight into the space; (ii) the reduction in electricity demand for lighting and (iii) the impact on peak heating and cooling demand and energy consumption. Although, there are many other parameters which should be taken into account when selecting window size, such as glare, thermal comfort, or even aesthetics, those should be evaluated at a second step, when shading devices are considered in the integrated design process.

2.1. Daylight availability ratio or daylight autonomy

A yearly daylighting analysis was performed in order to study the daylight availability in the space. Values of direct normal irradiance and diffuse horizontal irradiance were obtained using a TMY data file for Montreal and then processed by a solar radiation engine in TRNSYS in order to get corrected horizontal irradiance hourly values for one year. Then the Perez irradiance model (Perez et al., 1990) was used to predict beam and diffuse solar radiation on tilted surfaces, for the four major orientations. The Perez luminous efficacy models were then employed to predict beam and diffuse illuminance values incident on the façade, improving the results of a previous study (Tzempelikos and Athienitis, 2005). Assuming a double-glazed window with clear glass, the transmitted daylight was calculated for each hour in a year. Hourly transmittance values can be obtained as a function of solar incidence angle, which could eventually be expressed only as a function of day number and solar time, for convenience in hourly simulation. Then the hourly daylight distribution on the work plane during the year was calculated using a radiosity-based method (Athienitis and Tzempelikos, 2002). The simulation model predicts 8760 values of work plane illuminance for each point, window-to-wall ratio and orientation. Sample results are shown in Fig. 1.

Daylight availability ratio (DAR) – or daylight autonomy – is computed next as a function of orientation and window-to-wall ratio (WWR). DAR is defined as the fraction of working time in a year during which sufficient daylight (more than a pre-specified set point, e.g., 500 lx) is available on the work plane surface. It is calculated using the predicted illuminance values. This single number contains information about climate, orientation, room characteristics and fenestration optical properties and it can be used as a generalized index to describe the overall daylighting performance of a space with window(s). The daylighting module calculates daily, monthly and annual daylight availability ratio as a function of window-to-wall ratio for each major orientation in Montreal. The annual daylight availability ratio for each orientation is calculated as

$$\overline{\mathrm{DAR}}_{\mathrm{annual}} = \frac{\sum_{\mathrm{January}}^{\mathrm{December}} \overline{\mathrm{DAR}}_{\mathrm{month}}}{12} \tag{1}$$

The values presented in Table 1 describe the impact of sky conditions and window-to-wall ratio on daylight availability on a monthly and annual basis. This information can be used to characterize the daylighting performance of similar perimeter spaces in Montreal and could be a valuable source to designers/architects who design for daylight.

The annual average daylight availability ratio as a function of window-to-wall-ratio for each orientation in Montreal is plotted in Fig. 2. South-facing facades receive more

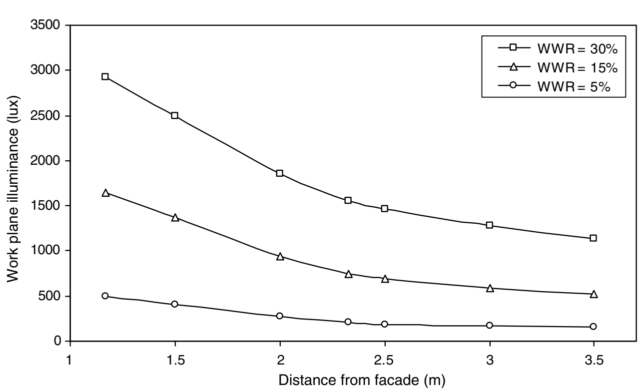

Fig. 1. Illuminance distribution on the work plane for three different window-to-wall ratios (south façade, June 30th, 2pm).

daylight than other orientations and therefore daylight availability for south facades is higher for any window size. For 30% window-to-wall ratio, natural daylight provides the space with 500 lux on the work plane for 76% of the working time in a year. Increasing window size more than 30% will not result in significant increase in useful daylight in the room (9% more for 80% window-to-wall ratio). Therefore this is identified as the daylighting saturation region for south-facing facades in Montreal and should be taken into account when selecting the glass ratio of a south-facing façade for daylight maximization.

The situation is similar for west-facing facades; 40% window-to-wall ratio gives 70% DAR. Choosing 50% of a west façade to be glass only increases daylight availability by 4%. East-facing facades receive less daylight during working hours and daylight availability levels are practically "stabilized" only for window-to-wall ratios higher than 50%. However, north-facing facades suffer from poor daylighting throughout the year; even for 20% window-to-wall ratio, the target work plane illuminance of 500 lux is never met and therefore electric lighting is required during all the working time. North-facing facades reach a "stable" daylighting condition after 50% window-to-wall ratio, but this is in conflict with thermal requirements, as explained later. All the curves of Fig. 2 could be described by a single equation using non-linear multivariate regression techniques; thus, the annual daylighting performance of any similar perimeter space in Montreal could be determined by using only one formula: DAR = f(WWR, orientation). Validation of daylighting results using Lightswitch software (Reinhart, 2005) is shown in Fig. 3. The differences are due to diverse approaches in calculating daylight availability ratio and different photocell arrangements.

2.2. Electric lighting consumption

The secondary link of electric lighting control is modelled in order to investigate the effect of window-to-wall ratio on electricity demand for electric lighting. A typical electric lighting system with T8 fluorescent lamps and 15 W/m^2 installed lighting power was assumed for the simulation. Two options were considered for electric lighting control:

(i) passive control (electric lights are always on during working hours) and
(ii) active on/off control (electric lights turn on/off based on occupancy sensors and work plane illuminance levels). When occupants are in the room and illuminance on work plane is less than 500 lux, lights turn on; in all other cases electric lights are automatically switched off.

For the case of passive control, the annual electricity demand for electric lighting is calculated from:

$$E_{\mathrm{L}} = P_{\mathrm{L}} \cdot t_y \cdot A \tag{2}$$

Table 1
Monthly and annual daylight availability ratio for major orientations in Montreal as a function of window-to-wall ratio

South WWR (%)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
5	0.13	0.05	0	0	0	0	0	0	0	0	0	0.08	0.02
10	0.33	0.25	0.33	0.4	0.28	0	0	0.2	0.55	0.45	0.2	0.13	0.26
15	0.53	0.4	0.6	0.65	0.6	0.45	0.68	0.68	0.7	0.6	0.3	0.28	0.54
20	0.63	0.53	0.65	0.68	0.8	0.78	0.88	0.93	0.8	0.7	0.42	0.35	0.68
30	0.73	0.58	0.8	0.83	0.9	0.85	0.9	0.94	0.9	0.73	0.5	0.45	0.76
50	0.8	0.62	0.85	0.9	0.95	0.9	0.93	0.96	0.95	0.77	0.55	0.5	0.81
80	0.82	0.64	0.88	0.93	0.97	0.94	0.96	0.98	0.97	0.8	0.6	0.55	0.84
North													
5	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0.05	0.08	0	0	0	0	0	0.02
30	0	0	0.15	0.08	0.18	0.45	0.68	0.18	0.13	0.05	0	0	0.16
50	0.28	0.25	0.73	0.73	0.88	0.9	0.9	0.88	0.78	0.53	0.18	0.13	0.6
80	0.5	0.4	0.82	0.9	0.95	0.95	0.95	0.93	0.85	0.65	0.4	0.3	0.72
East													
5	0	0	0	0	0.08	0.03	0	0	0.02	0	0	0	0.01
10	0.07	0.03	0.12	0.22	0.45	0.18	0.3	0.27	0.2	0.08	0	0	0.16
15	0.1	0.07	0.25	0.27	0.51	0.38	0.43	0.47	0.25	0.13	0	0	0.24
20	0.13	0.17	0.32	0.42	0.55	0.69	0.62	0.56	0.45	0.18	0.03	0.03	0.35
30	0.2	0.21	0.45	0.52	0.69	0.78	0.85	0.67	0.57	0.45	0.15	0.08	0.47
50	0.42	0.43	0.77	0.8	0.9	0.9	0.9	0.89	0.84	0.67	0.32	0.24	0.67
80	0.6	0.6	0.88	0.9	0.91	0.92	0.91	0.9	0.89	0.82	0.53	0.48	0.78
West													
5	0	0	0	0	0.13	0.05	0	0	0.03	0	0	0	0.02
10	0.1	0.05	0.18	0.33	0.68	0.28	0.5	0.4	0.3	0.13	0	0	0.24
15	0.15	0.1	0.38	0.4	0.78	0.58	0.65	0.7	0.38	0.2	0	0	0.36
20	0.2	0.25	0.48	0.63	0.83	0.88	0.9	0.85	0.68	0.28	0.05	0.05	0.5
30	0.35	0.33	0.6	0.75	0.95	0.95	0.95	0.92	0.8	0.65	0.23	0.13	0.63
50	0.5	0.5	.8	0.85	0.96	0.96	0.96	0.95	0.9	0.75	0.4	0.3	0.74
80	0.7	0.68	0.93	0.93	0.93	0.95	0.96	0.95	0.95	0.94	0.6	0.58	0.84

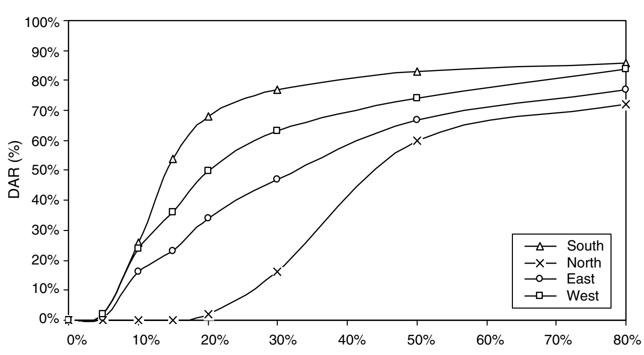

Fig. 2. Daylight availability ratio as a function of window-to-wall ratio for each orientation in Montreal.

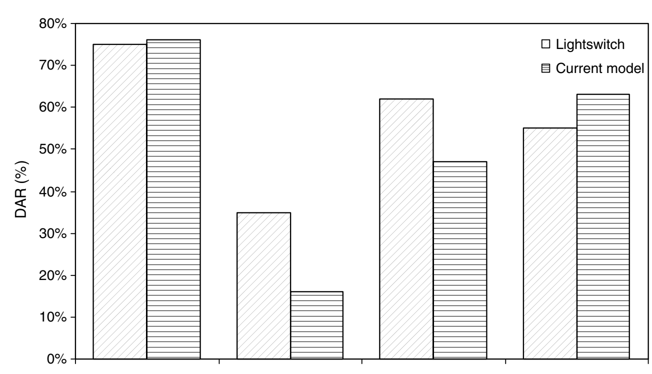

Fig. 3. Comparison of daylighting availability ratio results between Lightswitch software and the current daylighting simulation model.

where P_L is the installed lighting power (W/m^2), t_y is the number of working hours in a year and A is the floor area (m^2). The annual electricity demand for lighting is equal to 1800 MJ (112 MJ/m^{2}y) for the base case with passive lighting control. This value is independent of orientation and window size because electric lights are assumed to be continuously on. For the case of active on/off control, the electricity demand for lighting is directly calculated as a function of window-to-wall ratio for each orientation using the daylighting simulation results (Tzempelikos and Athienitis, 2005):

$$E_L = P_L \cdot t_y \cdot A \cdot (1 - \mathrm{DAR}) \tag{3}$$

in order to account for switching off of electric lights when at least 500 lux are incident on the work plane surface during working hours. Fig. 4 shows the impact of window-to-wall ratio on electricity demand for lighting, for different orientations. Following the daylighting simulation results, electricity demand for lighting assuming active control decreases with window-to-wall ratio for all orientations. South-facing facades have higher DAR and therefore less energy is required for lighting the space. For 30% WWR, annual electricity demand for lighting is already reduced by 77% (from 1800 MJ to 413 MJ) compared to passive lighting control and practically it is not further reduced for larger window areas. For north-facing facades, the electricity demand for lighting remains at 1800 MJ for window-to-wall ratios less than 20% because work plane illuminance never reaches 500 lux for small glazing areas.

It is also possible to develop correlations between performance indices when they are calculated as a function of the same design variable (e.g., window-to-wall ratio). For example, Fig. 5 shows the annual electricity demand for lighting as a function of daylight availability ratio. The correlation between electricity demand for lighting and DAR for the south-facing case is ($R^2 = 1$):

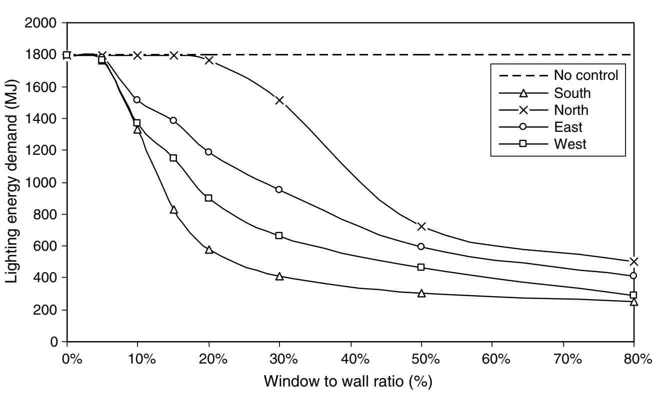

Fig. 4. The impact of window-to-wall ratio on annual electricity demand for lighting, for different orientations. No control refers to passive lighting control.

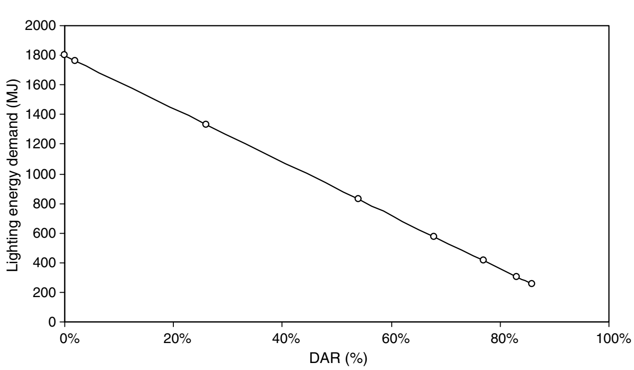

Fig. 5. Correlation between electricity demand for lighting and daylight availability ratio for a south-facing perimeter space of the base case, assuming active on/off electric lighting control.

$$E_L = -1797.5 \cdot \mathrm{DAR} + 1797.2 \tag{4}$$

Designers may consult Table 1 for daylighting results and then evaluate the impact of daylighting in electricity demand for lighting using Eq. (4). Alternatively, Figs. 2 and 4 can be used as graphical tools.

2.3. Impact on cooling energy demand

A thermal network approach was used in order to simulate the thermal performance of the considered office space. Convection and radiation heat transfer were modelled separately in detail. For convection between interior surfaces and room air, the Energy Plus (2004) equations for interior convection were used. For the exterior heat transfer coefficient, the advanced Energy Plus approach is followed, which is a combination of the MoWitt and BLAST (DOE-2) convection models. The total exterior coefficient is the sum of the convective and the radiative coefficients, where the exterior convective coefficient is calculated as the sum of the natural and forced convection taking into account outside temperature, wind speed and surface roughness. The radiative exterior coefficient is calculated from the surface emissivity, the temperature of the sky and the ground and the respective view factors. Radiation between all interior surfaces is modelled in detail using the radiosity method. Radiation view factors between surfaces are used and radiation heat exchange is represented with non-linear heat transfer coefficients. Heat storage in walls is modelled by placing one or more thermal capacitances in thermal mass nodes, depending on the material and the desired degree of detail. Solar gains are calculated accurately in order to model the impact of climate and fenestration on interior conditions of perimeter spaces. Using the hourly horizontal data from a TMY weather file, the Perez irradiance model (Perez et al., 1990) is used to predict hourly diffuse irradiance on a tilted surface (window). The transmission of solar radiation in the room is done in the same way as for daylight. Transient hourly values of window solar transmittance are calculated to be used in the thermal simulation model. The amount of heat captured in glazings and released to room air is also computed.

Internal gains from lights, appliances and people are also modelled on an hourly basis. Occupancy and lighting operation schedules and time-based control of shading devices (if any) are all included in the simulation algorithm using an explicit form of the equations. This is a critical characteristic of the simulation process; it will reveal the impact of control on the overall performance.

An energy balance is then applied at each node at regular time steps, in order to obtain the temperature of the nodes as a function of time. One thermal node is used for room air, except if the mixing of two air masses occurs. When all thermal resistances and heat sources have been calculated, a simulation time-step (Δt) is selected based on a numerical stability criterion. Then all the hourly variables are evaluated for each time step, using a time series method or Fourier transform. The system of simultaneous differential and algebraic non-linear equations can be solved numerically using an explicit finite difference technique, in which we march forward in time from a set of initial conditions. The general form of the explicit finite difference model corresponding to node (i) and time step (p) is (Athienitis and Santamouris, 2002):

$$T_i^{p+1} = \frac{\Delta t}{C_i} \cdot \left\{ q_i + \sum_j \frac{(T_{\mathrm{j}}^{\mathrm{p}} - T_{\mathrm{i}}^{\mathrm{p}})}{R_{\mathrm{ij}}} \right\} + T_i^p \qquad (5)$$

where T is temperature, ($p + 1$) indicates next time step, (j) represents all nodes connected to node (i), R_{ij} is the thermal resistance connecting nodes (i) and (j), C_{i} the capacitance of node (i), if any, and q is a heat source at node (i).

The impact of window-to-wall ratio on thermal performance indices was studied by running the thermal simulation as a function of window-to-wall ratio. The simultaneous impact of daylighting on thermal performance indices is modelled by consistently passing information from the daylighting and electric lighting simulation to the thermal module on an hourly basis, considering window-to-wall ratio as a design variable. Hourly internal gains from lights and people are modelled as a separate source based on occupancy schedules and reading the daylighting and electric lighting simulation results as a function of window-to-wall ratio.

For the base case, the maximum allowed time step is five minutes. Thermal simulation runs on a 5-min time step and therefore the values of all simulation parameters must be re-evaluated every 5 min. Transformation from hourly values to 5-min calculations was achieved by modelling of all parameters with discrete Fourier series and then applying an inverse Fourier transform for the new (5-min) time step. The system of simultaneous finite difference heat balance equations is then solved iteratively in matrix form and as a function of window-to-wall ratio. Heating and cooling energy demand are calculated by integrating thermal loads over time on a daily, monthly or yearly basis. Energy consumption for heating and cooling could be evaluated if a particular HVAC system with a certain coefficient of performance is selected. Table 2 shows heating and cooling load results for different orientations.

Fig. 6 provides all the necessary information for the impact of window-to-wall on integrated daylighting and thermal performance and a selection region is identified. A glazing area of 30% satisfies daylighting requirements (daylight availability reaches 76%) and the respective effect on thermal performance indices is shown. The above results also indicate that, for south-facing facades in Montreal, larger window areas would only result in higher energy demand for heating and cooling without improving thermal or visual interior conditions and therefore window-to-wall ratios above the selection region should be chosen only for aesthetics purpose according to the overall architectural envelope design of the building. Validation of thermal results is presented in Fig. 7. The results presented next refer to 30% window-to-wall ratio for a south-facing perimeter space.

The impact of electric lighting control on monthly cooling, heating and lighting energy demand is separately shown in Figs. 8–10. Lighting energy demand (Fig. 8) is drastically reduced even during the winter, when daylight availability is low because of snowfall and overcast conditions. This effect is taken into account when calculating

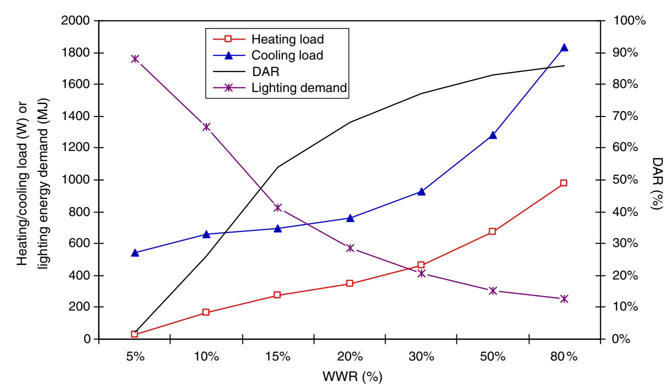

Fig. 6. Integrated performance indices as a function of window-to-wall for a south-facing perimeter space of the base case, assuming active on/off electric lighting control. The impact of daylight is included in the thermal calculations.

Table 2
Heating and cooling load as a function of window-to-wall ratio for each orientation

Orientation	South		North		West	
WWR (%)	Heating load (W)	Cooling load (W)	Heating load (W)	Cooling load (W)	Heating load (W)	Cooling load (W)
0	220	342	228	317	223	333
5	224	348	233	319	227	339
10	316	514	342	338	325	463
15	365	606	400	358	378	536
20	414	698	458	378	431	608
30	498	882	574	408	539	754
40	610	1067	690	463	647	902
50	709	1251	806	508	755	1049
60	808	1436	922	548	862	1195
70	908	1621	1038	598	973	1343
80	1007	1806	1154	648	1082	1489

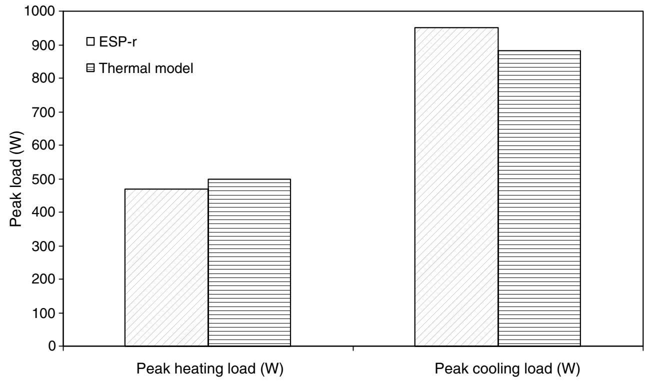

Fig. 7. Comparison of peak heating and cooling load results between ESP-r and the current thermal simulation module.

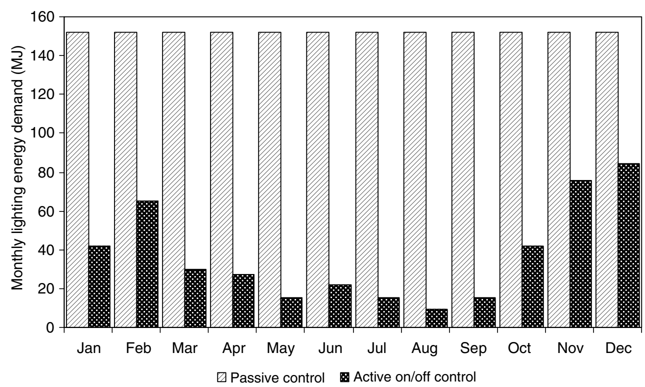

Fig. 8. The impact of electric lighting control on monthly lighting energy demand.

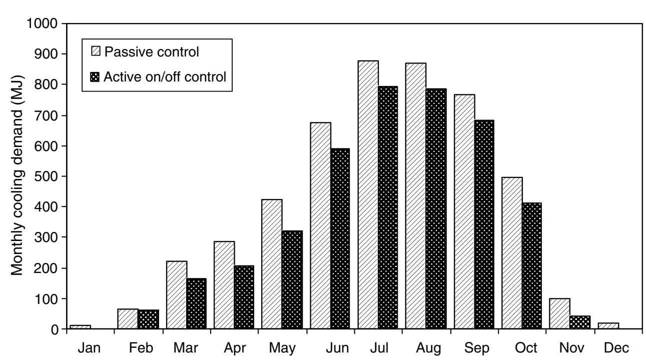

Fig. 9. The impact of electric lighting control on monthly cooling energy demand.

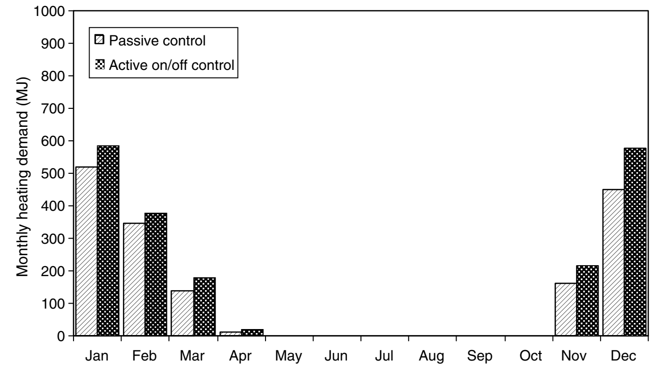

Fig. 10. The impact of electric lighting control on monthly heating energy demand.

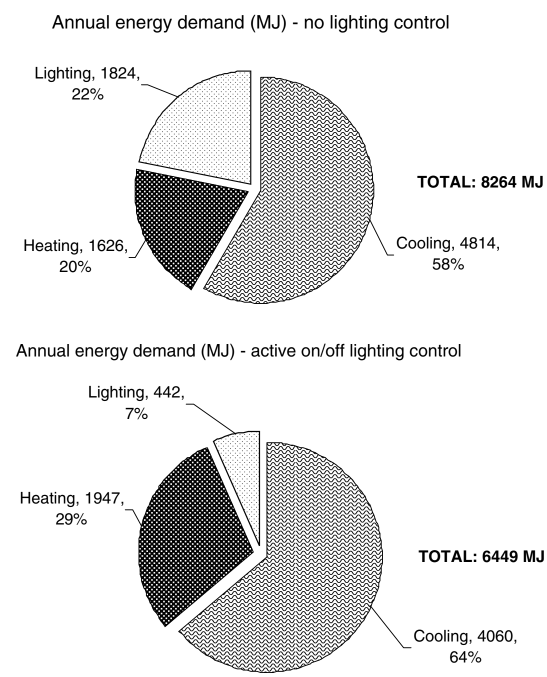

Fig. 11. The overall impact of electric lighting control on annual energy demand.

monthly cooling and heating energy demand in Figs. 9 and 10. Cooling energy demand is reduced during the year if active lighting control is used due to reduction in internal gains. On the contrary, heating energy demand is slightly increased (during the winter) when the lights are controlled. Interestingly, Fig. 9 shows that cooling is required throughout the year, even during the winter season.

The overall combined impact of daylighting and electric lighting control on annual energy demand for heating, cooling and lighting is shown in Fig. 11. Active on/off control results in 16% increase in annual heating demand (from 1626 MJ to 1947 MJ), 16% decrease in annual cooling demand (from 4814 MJ to 4060 MJ) and 76% decrease in annual lighting demand (from 1824 MJ to 442 MJ). Although the relative percentage of each component change, the total annual energy demand is reduced by 22% (from 8264 MJ to 6449 MJ) if active on/off electric lighting control is enabled.

Despite the fact that the building is located in Montreal, the perimeter space considered in the integrated analysis is rather cooling-dominated. Monthly comparison of energy demand components for the recommended case is shown in Fig. 12. For February, March and November both cooling and heating is needed. Energy demand for heating could be reduced if a window with higher thermal resistance (>0.4 m^2 °C/W) is used.

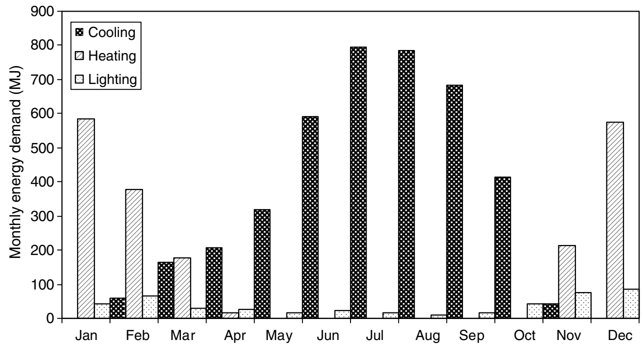

Fig. 12. Comparison of monthly energy demand for heating, cooling and lighting for the selected case (30% window-to-wall ratio, south-facing, active on/off electric lighting control).

3. The impact of shading

Maximization of daylight usage is desired because visual quality is ensured, occupants' productivity is increased and electricity consumption for lighting is reduced. Nevertheless, daylight is only the visible portion of solar radiation. Glazing products become sources of radiant heat by transmitting solar radiation and by emitting long-wave radiation to dissipate some of the absorbed solar energy. Moreover, problems associated with glare and visual discomfort are inevitable when direct solar radiation is transmitted into the room. For office spaces, it is suggested that direct sunlight is not allowed to enter the room, to avoid overheating and glare problems. Shading provision is therefore necessary in order to prevent thermal and visual discomfort.

Climatic conditions and daylight availability play a major role in the design and control of a shading system. The location, properties and control of the shading device have a significant impact on both daylighting and thermal performance of perimeter office spaces. Simplified modeling methods for shading have proven to be inaccurate in the prediction of thermal and daylighting impact (ASHRAE, 2001). The most effective means of establishing fenestration and shading annual energy performance is through detailed, dynamic, hourly computer simulations for the specific building and climate of interest.

3.1. Selection of shading device properties and control based on integrated thermal and daylighting simulation – exterior roller shades

This section presents an application of the integrated methodology for the case of exterior roller shades (commonly used as shading layers) on a south-facing façade with 30% glass. The roller shade solar and optical properties and the shading control are direct links between daylighting and thermal performance and are now considered as design variables. For an exterior shade, its absorptance and reflectance have negligible effects on interior conditions; the important parameter is the transmittance (visible and solar). It will determine the amount of transmitted daylight into the room and the incoming solar gains. Daylighting simulation is therefore performed as function of shade transmittance for each control option. First, the transmitted beam and diffuse daylight into the room for every hour in a year is calculated by multiplying the beam and diffuse components of window and shading device visible transmittance, respectively, taking into account inter-reflections between the shade and the glazing. Roller shades are simulated as perfect diffusers with constant transmittance. Although this assumption could be valid for low transmittance values, it leads to errors for higher values and different shade materials. Software such as WIS (van Dijk, 2002) or bi-directional transmittance measurements (Andersen et al., 2005) can be used, however, as input in the transmission model to account for variable transmission characteristics. However, in the early design stage for which this analysis is performed, this degree of detail may be unnecessary, except if the transmittance of the shading system has a very strong dependence on incident solar angles (even then, after a large number of inter-reflections the error is reduced). The transmitted daylight into the room for each hour in the year is calculated as follows:

$$D = \frac{E_b \cdot \tau_b + E_d \cdot \tau_d}{1 - \rho_{rs} \cdot \rho_w} \cdot \tau_{rs} \quad (6)$$

where τ_b is the beam window transmittance, τ_d is the diffuse window transmittance, τ_{rs} is the roller shade transmittance, ρ_w is the window reflectance and ρ_{rs} is the roller shade reflectance. All the above parameters are essentially expressed as a function of time (solar incidence angle). The denominator accounts for inter-reflections between the exterior shade and the window.

Two types of shading control were considered:

(i) passive control: roller shade remains closed during working hours to ensure privacy/reduce glare;
(ii) active automatic control: roller shade is open when beam illuminance on the window is negligible (or beam solar radiation incident on the window is less than 20 W/m^2). For each working hour in the year during which the above condition is satisfied, the roller shade opens automatically for maximization of daylight and view to the outside (without causing glare, since there is no direct sunlight).

Shading control is simulated by modelling the transmittance equations as schedule functions. For passive control, the transmittance of the roller shade is always equal to τ_{rs}. For automatic active shading control, the shade transmittance is set equal to τ_{rs} when beam illuminance on the window is higher than a minimum and equal to one when no direct sunlight is incident on the window (or less than a threshold-200 lux). An example of shading control modelling using transmittance schedules is shown in Fig. 13 for five successive days in February. In this case, the transmittance was set to 10% (shade closed) if more than 200 lux of

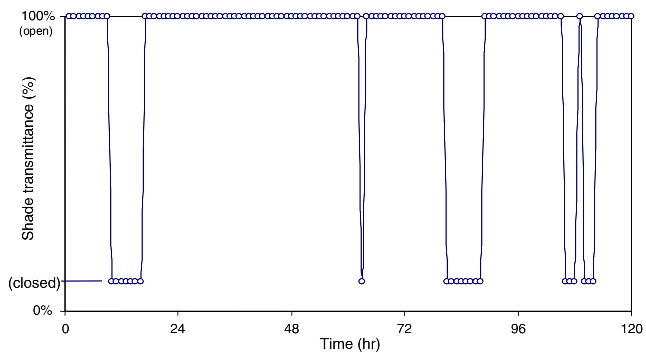

Fig. 13. Example of roller shade transmittance schedule for modelling shading control (five successive days in February). Whenever there is excessive sunlight, the roller shade (10% transmittance) automatically closes in order to protect from glare.

beam daylight were incident on the window during working hours (9am–5pm). In all other cases (shade open) it was set equal to one – only the glazing transmittance was used. Obviously, the first day is clear and the roller shade is closed to prevent from glare. The second day is cloudy and, therefore, the shade remains open throughout the day to maximize diffuse daylight utilization. The last day shown is an interesting case; mixed sky conditions occur and the shade is automatically closed for an hour (1pm) because during that time direct sunlight was incident on the window. Then clouds move in front of the sun again and only diffuse daylight is present, thus the shade automatically re-opens.

Shading control is modelled in the way described above and also as a function of shade transmittance. A radiosity-based method is again employed and hourly work plane illuminance is computed. Daylight availability ratio is calculated in the same way as before, but now it is plotted as a function of shade transmittance for the different control options. The results of the daylighting simulation (Fig. 14) include the impact of hourly sky conditions and shading transmittance and control. One of the simultaneous goals is to prevent direct sunlight from entering the space, for glare elimination; however, this depends on shade transmittance. The impact of control on the daylighting performance index is clearly shown: passive shading control results in poor daylight availability while simple on/off (open/close) control of the shade during working hours – depending on daylighting conditions – increases annual daylight availability ratio by 20% on average. The variation of the daylight availability ratio with shade transmittance indicates that the new daylighting saturation region occurs for a shade transmittance equal to 20%, for both shading control options. For this value, active automatic shade control results in 20% more annual daylight availability ratio (60%) compared to passive shading control (40%). This means that people could work for 20% more time in a year without using electric lighting (only by using daylight). Except for energy savings, this translates in possible increase in productivity (Heschong, 2002).

Shading properties and control also have a direct impact on electricity demand for lighting. Assuming active on/off lighting control (based on previous results), the electricity demand for lighting is calculated from the daylighting analysis results as a function of shade transmittance and control (Fig. 15). Passive shading control results in higher energy demand for any transmittance value because daylight availability is reduced. Lighting energy demand is not significantly decreased for shade transmittance higher than 20%. For 20% transmittance, annual electric lighting energy demand is already reduced by 40% for passive shading control and by 60% for active automatic shading control (compared to passive lighting control).

The impact of shading links on the thermal performance is presented next. The shade transmittance has a direct effect on the solar gains transmitted into the room and therefore on the thermal performance of the space. Moreover, it has a direct impact on the daylight availability and electric lighting energy demand; therefore it also has another indirect impact on thermal performance indices. The hourly thermal simulation module runs as a function of shade transmittance and control. The impact of shading control on transmitted solar radiation is modelled with schedule functions of shade transmittance as described

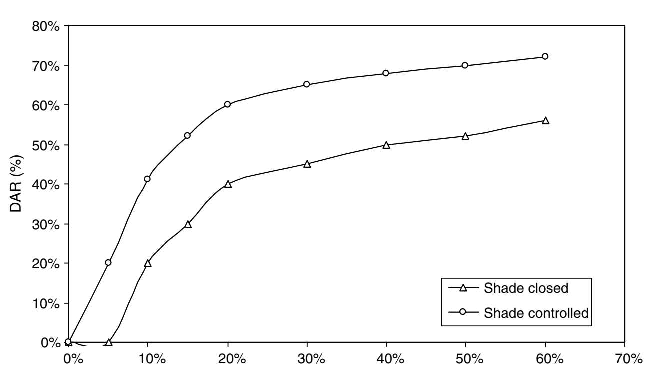

Fig. 14. Annual daylight availability ratio as a function of exterior shade transmittance for the two different shading control options.

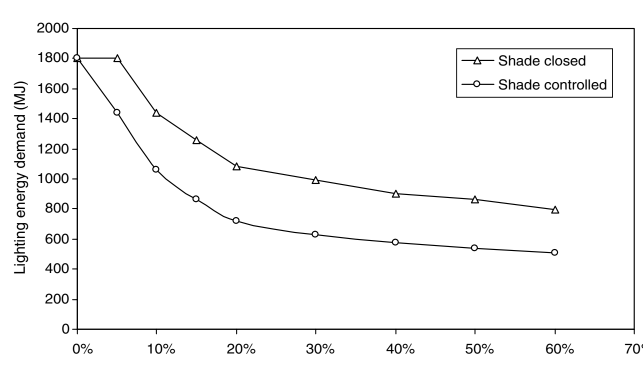

Fig. 15. The impact of shading transmittance and control on lighting energy demand.

above. The secondary impact of shading properties and control on lighting internal gains is modelled using schedule functions for the internal gains source in the thermal network. Based on the daylighting and electric lighting simulation results, hourly information is passed to the thermal simulation module for the same hour in order to include the effect of daylighting on thermal performance as a function of the shading design variables. Internal gains from lights are therefore predicted as a function of roller shade properties for each working hour, taking into account the impact of shading control. Representative results for a day in February are shown in Fig. 16. In this case, the transmittance of the shade was set to 10% when beam sunlight was incident on the window and active automatic shading control was simulated in conjunction with active on/off lighting control. Mixed sky conditions result in on/off operation of electric lights depending on work plane illuminance values, which eventually depend on shade transmittance and control. The results of Fig. 16 indicate that at 10am (as well as at 3pm–5pm) electric lights were on, which means that (i) either sky conditions were overcast and there was not enough daylight on the work plane or (ii) that beam daylight was incident and the shade automatically closed so daylight levels on the work plane surface dropped below 500 lux and electric lights automatically switched on.

Cooling energy demand is plotted as a function of shade transmittance, taking into account active automatic shading and lighting control. The results are presented in Fig. 17. Cooling energy demand is slightly reduced for shade transmittances between 10% and 20%, because for those values there is enough available daylight in the space and electric lights are efficiently controlled. Then, it increases because large solar gains are admitted in the space. The curve that shows the sum of cooling and lighting energy demand is possibly the most important. Since shading is used to reduce cooling requirements (except for glare), this is the curve that shows the integrated benefits of daylighting, shading and electric lighting control. This key integrated performance measure, shown separately in Fig. 18, indicates that optimum energy performance is only achieved if daylighting benefits due to reduced electric lighting operation (and the subsequent reduction in cooling requirements) exceed the increase in energy demand due to increased solar gains, which is always affected by shading control. The variation of this index with shading properties helps in investigating if this optimal region exists (Tzempelikos, 2005). Fig. 18 shows that, for the considered case, it exists and it occurs for a roller shade transmittance equal to 20%. For smaller transmittance values, poor daylighting conditions result in large internal gains due to continuous electric lighting operation during working hours; therefore both cooling and lighting demand increase (the cost of cooling and lighting energy consumption is of course different). For higher transmittance values, daylight availability is adequate but excessive solar gains result in an increase of cooling demand which is higher than the reduction due to reduced internal gains. Active automatic shading and lighting control make it possible for this integrated performance index to reach a minimum for a certain roller shade transmittance value (20%) that can be selected from Fig. 18.

Since maximization of daylight utilization is also a criterion when selecting shading properties (and control), one

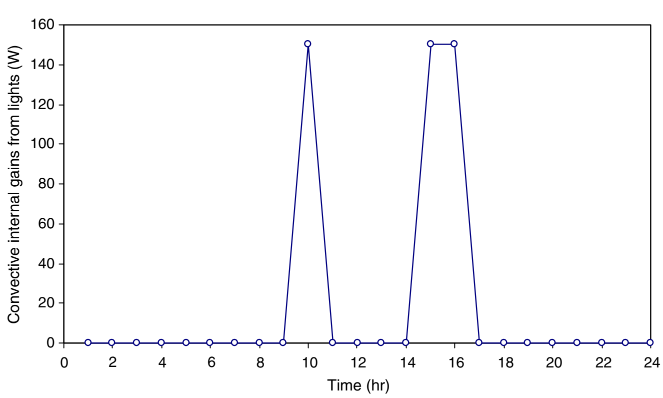

Fig. 16. Hourly internal gains from electric lights during working hours assuming active automatic shading and lighting control.

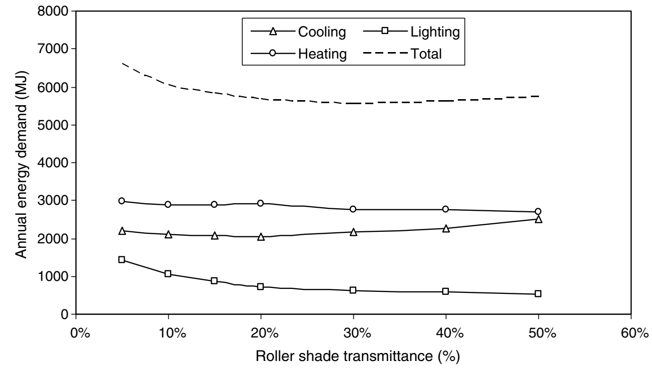

Fig. 17. Integrated thermal and lighting performance indices as a function of shade transmittance, assuming active automatic shading and lighting control.

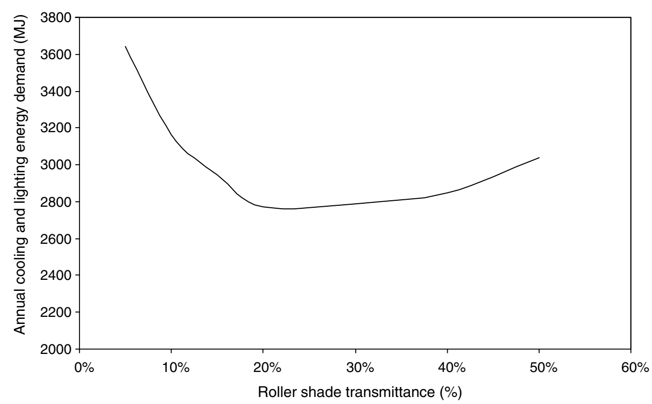

Fig. 18. The sum of annual cooling and lighting energy demand – a key integrated performance measure – as a function of roller shade transmittance. The curve reaches a minimum for $\tau_{rs} = 20\%$.

also has to examine if the considered region coincides with the saturation region from daylighting simulation results of Fig. 14. Basically, the two regions overlap if the curve of Fig. 18 really reaches a minimum (which is not always the case). An interesting point is that, although the total annual energy demand (loads only) also reaches a minimum (for $\tau_{rs} = 30\%$), this value does not match exactly with the daylighting saturation region, neither with the minimization of cooling and lighting energy demand. Furthermore, the annual energy demand is not necessarily minimized for heating-dominated climates, especially for non-south-facing facades (for any type of shading and lighting control). Shading devices are not used for reduction of heating requirements; they are used for rejection of major solar gains – to reduce peak cooling load and cooling energy demand – as well as for glare elimination and possible simultaneous daylight maximization. For the case considered here, a shading layer with 20% average transmittance can minimize cooling and lighting energy demand (not consumption) while at the same time daylight availability is maximized if active shading and lighting automatic control is utilized. The results include simulation of shoulder seasons when heating may be required for part of the day (e.g., early morning) and cooling later on in the afternoon. For warmer climates, the optimum would shift to the left (smaller transmittance values), since cooling energy would be much higher. Moreover, the actual total energy consumption could be clearly minimized for cooling-dominated climates. Another possibility not considered here is transferring solar gains from a south-facing to a north-facing zone or between perimeter and interior zones with heat pumps.

New correlations between integrated performance indices can be developed, taking into account the impact of shading control. Fig. 19 shows the variation of lighting and cooling energy demand with daylight availability ratio, for the case of active lighting/shading control. Cooling demand is minimized when daylight availability ratio reaches 60%, because for this condition solar and internal gains are optimally balanced, assuming automatic control. Lighting energy demand decreases when daylight availability is increased (higher transmittance values), and the integrated impact of shading properties and control transforms Eq. (3) into a second degree polynomial ($R^2 = 0.9995$):

$$E_L = -868.55 \cdot \mathrm{DAR}^2 - 819.17 \cdot \mathrm{DAR} + 1532.4 \qquad (7)$$

Fig. 20 presents cooling energy demand as a function of lighting energy demand, assuming lighting and shading automatic control. The respective transmittance values are also shown. For 20% transmittance, which corresponds to 720 MJ lighting energy demand, the impact of shading control results in minimization of cooling demand (2054 MJ) based on the integrated analysis. This value corresponds to 60% DAR, for which solar and internal gains are optimally controlled. Based on the variation of performance indices with shading design variables, it is recommended that 20% transmittance is selected for an exterior roller shade for a south-facing façade with 30% window-to-wall ratio in Montreal, to simultaneously satisfy the thermal and daylighting requirements. The annual energy demand breakdown is shown in Fig. 21, and the annual energy consumption breakdown is presented in Fig. 22. Shading operation results in increased heating demand – which now accounts for 51% of the total – while cooling demand is further reduced to 36% of the total annual energy demand.

A general comparison of the integrated daylighting and thermal analysis results (including the shading impact) with

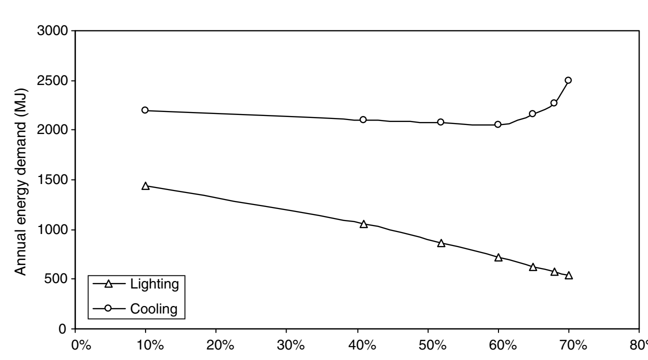

Fig. 19. Correlations between daylighting, electric lighting and thermal performance indices taking into account the impact of automatic shading and lighting control.

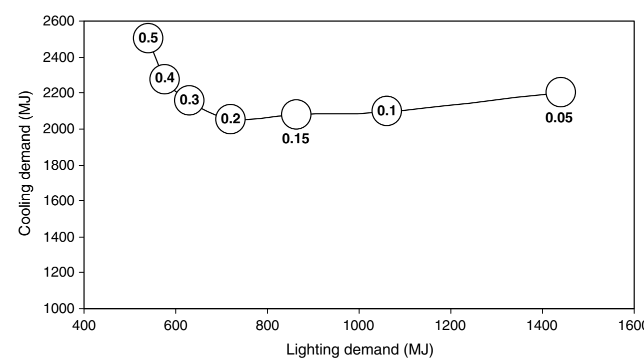

Fig. 20. Correlation between cooling and lighting energy demand taking into account the impact of automatic shading and lighting control. The respective roller shade transmittance values are shown.

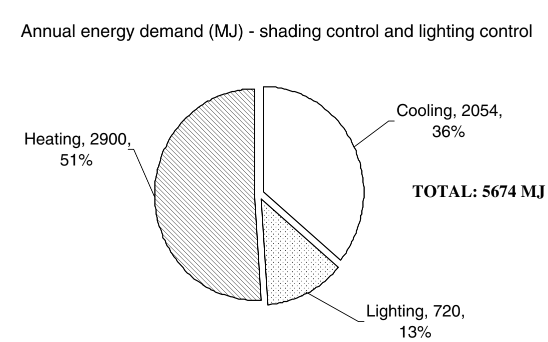

Fig. 21. Annual energy demand breakdown using an exterior roller shade with 20% transmittance and active automatic lighting and shading control.

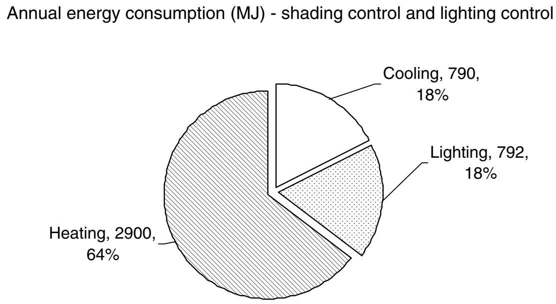

Fig. 22. Annual energy consumption breakdown using an exterior roller shade with 20% transmittance and active automatic lighting and shading control.

the base case (30% window-to-wall ratio) and passive and active electric lighting control is presented in Fig. 23. Shading control has the highest impact on cooling energy demand, which is drastically reduced by almost 50% (from 4060 MJ to 2054 MJ) compared to active lighting control without shading. Lighting energy demand is of course mostly affected by lighting control and increases by 38% (from 442 MJ to 720 MJ) if automated shading is used because of the relative decrease in daylight availability (although shading control takes into account daylight maximization). However, utilization of an exterior shade with 20% transmittance and active automatic control results in reduction in total annual energy demand by 12% (from 6449 MJ to 5674 MJ). This happened because:

(i) cooling is more important than heating for similar south-facing perimeter spaces;
(ii) the energy benefits of daylighting, with active automatic shading and lighting control, were higher than the penalty due to increase of solar gains (for 20% shade transmittance) and an optimum balance between controlled solar gains and internal gains can be achieved (Fig. 18).

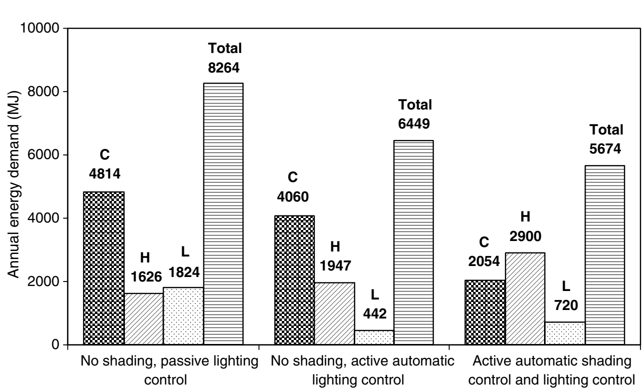

Fig. 23. Comparison between annual heating, cooling, lighting and total energy demand for the base case with passive and active lighting control and the studied roller shade case with the selected transmittance and control.

Note that the daylighting criterion for maximization of daylight utilization is satisfied by choosing the right control strategy and by selecting the daylight saturation region (Fig. 14).

Although 20% transmittance value satisfies daylighting and cooling requirements, it is expected that a roller shade with 20% transmittance would create glare problems. Transmittance values higher than 5% cannot ensure glare elimination. The 20% value should therefore represent the average transmittance of the shading device, which can vary along the height of the shade. A solution to this inconvenience is the separation of window area in two parts. The bottom part should have a lower transmittance than the upper part to protect from glare, but the average should approach 20%. For example, this could be achieved using venetian blinds in the upper part, or a roller shade with variable transmittance based on a three-section façade concept (Tzempelikos and Athienitis, 2003).

4. Conclusion

This paper presented the results of a simulation-based integrated thermal and daylighting analysis for perimeter office spaces. The objectives was to (i) to evaluate the impact of façade design alternatives – glazing area and shading properties and control – on the thermal and daylighting performance of office buildings at the early design stage and (ii) to provide guidelines on selecting glazing area and shading properties at this preliminary stage.

Considering a typical perimeter office in Montreal as a base case, the impact of window-to-wall ratio on visual and thermal performance and electric lighting usage was investigated. The daylighting performance of a window was expressed with annual daylight availability ratio, a generalized parameter that includes the effects of climate, orientation and window optical properties. The impact of daylighting and electric lighting control on thermal performance was simulated as a function of window-to-wall ratio for different orientations. It was found that, for south-facing facades, 30% window-to-wall ratio could ensure that natural daylight provides the space with 500 lux on the work plane for 76% of the working time in a year. Larger window areas will not result in significant increase in useful daylight in the room; therefore this is identified as the daylighting saturation region for south-facing facades in Montreal and should be taken into account when selecting glass ratio of a south-facing façade for daylight maximization. Also, active automatic on/off lighting control results in 77% reduction in electricity demand for lighting and 16% reduction in annual cooling demand, for 30% window-to-wall ratio.

Even in heating-dominated climates, cooling is important for perimeter spaces with high solar gains. Shading provision is necessary; the properties and control of shading have to be taken into account from the early design stage, since they have a significant impact on peak thermal loads, energy consumption for heating, cooling and lighting, as well as on human comfort. An exterior roller shade was used as an example of integrated analysis. Simulation runs as a function of shade transmittance and two different types of control, in conjuction with electric lighting control for 30% window-to-wall area. It was shown that for 20% transmittance, simultaneous control of a shading device and a controllable lighting system on a south-facing façade could lead to minimization of energy demand for lighting and cooling, and maximization of daylight utilization. Comparing with the base case without shading, shading control (20% average transmittance over the facade) accounts for 50% decrease in annual cooling energy demand. Although electric lighting demand is increased, affected by shading patterns, an optimal balance between solar gains and internal gains is achieved and the total annual energy demand is also reduced by 12%. Correlations between performance indices could be used to further characterize the role of each parameter in this integrated process.

The interaction with the HVAC system was not considered enough in this work – the emphasis was on modeling the impact of shading on building energy demand (thermal loads). The actual energy consumption will depend on the type and operation of the HVAC system, as well as on the particular control strategies followed in perimeter zones, which are affected by solar gains and fenestration characteristics. The cost of electricity consumption for cooling and lighting is different and depends on the performance and operation of the cooling system. More research is planned towards this direction, in order to consider the HVAC components' operation and control for solar optimization of perimeter zones, taking into account the daylighting and shading impact.

Moreover, simulation results imply that the properties of shading systems (if not the type) should vary with orientation; the performance indices are very sensitive to orientation and climate. For warmer climates, results would tend to shift to smaller values for window-to-wall ratio and shading transmittance, with higher energy benefits. Finally, this type of detailed integrated analysis should be performed during the early design stage, when critical decisions will have a major impact on the energy performance during the lifetime of the building.

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